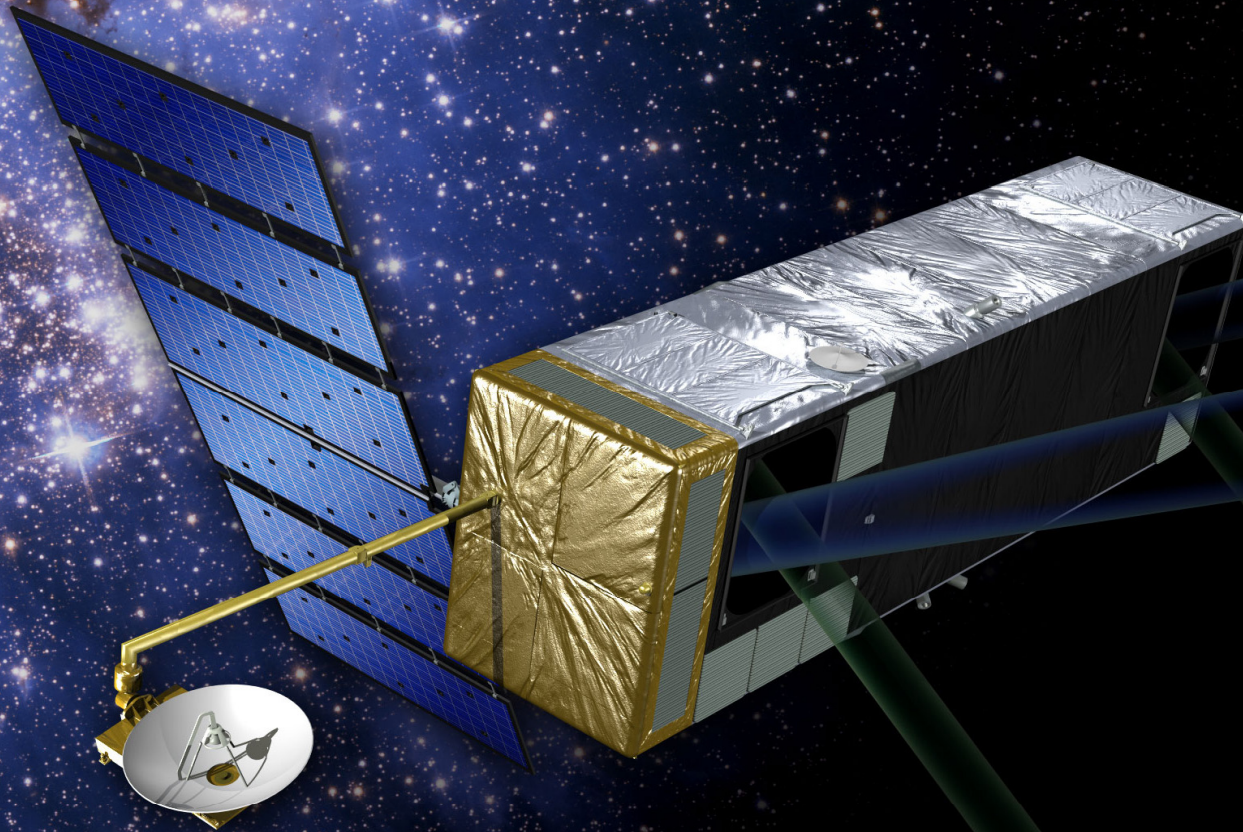


# Interferometric Search for Exo-Earths



M. Shao JPL



## Outline



SIM PlanetQuest

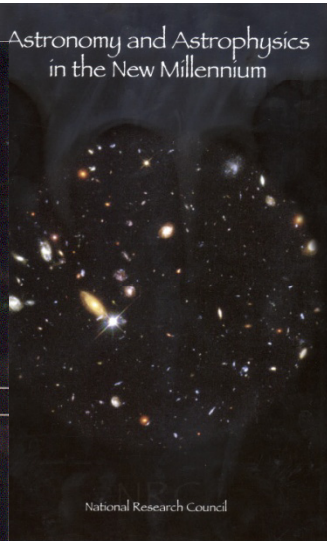
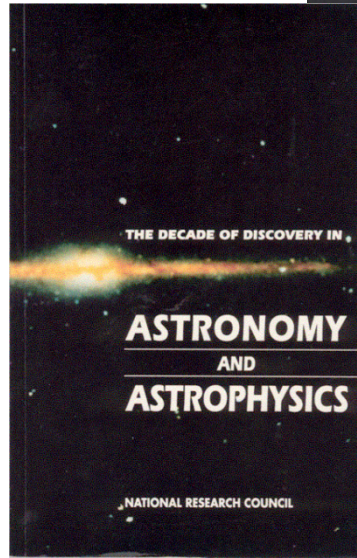
- Interferometer and astrometry
- SIM picture
  - Guide interferometers, external met
- SIM exoplanet detection capability (for 1 Mearth @ 1 AU)
  - Other SIM exoplanet science
- Brief overview of astrophysics with SIM
- Change from SIM to SIM-LITE
  - 6m, 50cm,
- Technology milestones
  - List of milestones
- Systematic errors and floor
- Applications of picometer metrology to direct detection of Exoplanets



## Recommended by the NRC



SIM PlanetQuest



## 1990 and 2000 NRC Decadal Reviews

“...emphasized the dual capability of SIM, noting that this capability would enable “...*both... detecting planets and ... mapping the structure of the Milky Way and other nearby galaxies.*”

Concept	Wide-Angle Astrometry		Narrow-Angle Astrometry				
	Requirement ( $\mu$ as)	Goal ( $\mu$ as)	Requirement ( $\mu$ as)	Goal ( $\mu$ as)	Magnitude Limit (V)	Nulling?	Synthesis Imaging?
1991 AASC (AIM)	30	3	-	-	20	No	No
2001 AASC (SIM)	10	4	3	1	20	Yes	Full UV plane from 1 to 10 m
2002 CAA Assessment*	30	4	3	1	20	No	10 m baseline only (plus rotation)
SIM-Lite	4 $\mu$ as		1.0 $\mu$ as		20		

\* J.H. McElroy (chair, SSB) & J.P. Huchra (chair BoPaA), CAA assessment of SIM redesign in letter to Dr. E. Weiler (AA for Space Science), 9/12/2002)

\*\* Current (Feb 2007) performance prediction, without margin.



# Astrometry with an Interferometer



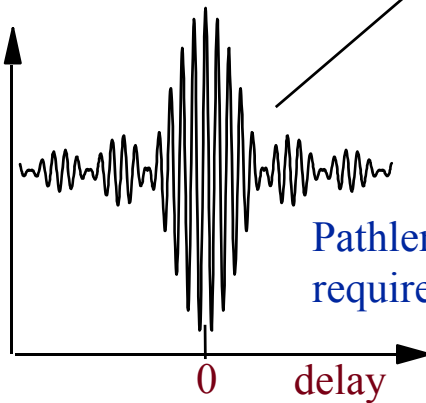
SIM PlanetQuest

$$\text{Delay} = \underline{\mathbf{B}} * \mathbf{S} + c$$

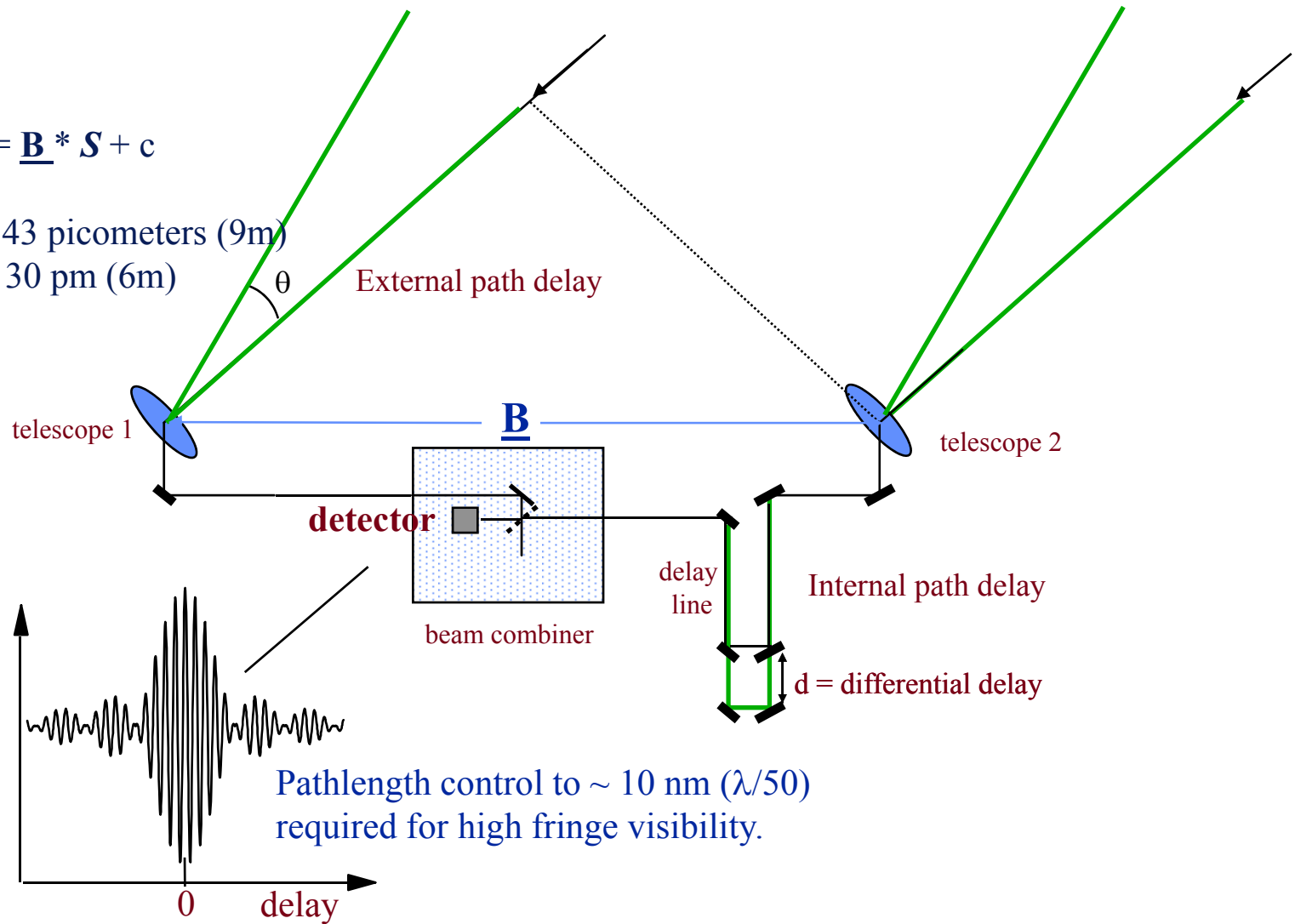
$1 \mu\text{s} \sim 43 \text{ picometers (9m)}$

$\sim 30 \text{ pm (6m)}$

detected  
intensity



Pathlength control to  $\sim 10 \text{ nm } (\lambda/50)$   
required for high fringe visibility.

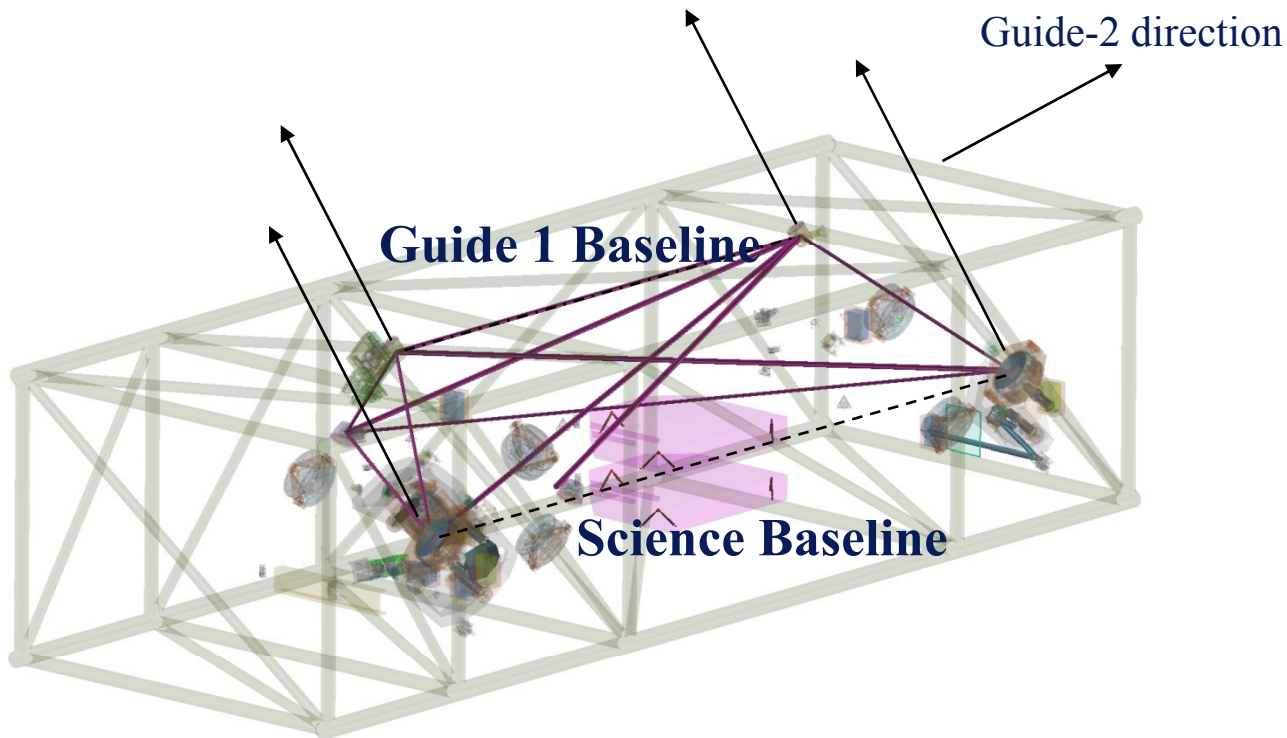




# Stabilizing the Baseline/Guide Interferometer(s)



SIM PlanetQuest



The baseline vector must be stable (in knowledge), as the science interferometer observes a number of stars.

Rotation of the baseline in inertial space was monitored (in the original SIM design) by two guide interferometers looking at two guide stars  $\sim 90^\circ$  apart.

Guide-1 needs  $\mu\text{as}$  precision. But guide-2 can be much less precise. For narrow angle astrometry, with a  $1^\circ$  field, guide-2 precision is relaxed to  $\sim 50 \mu\text{as}$ . SIM-“lite” uses a  $\sim 30\text{cm}$  telescope looking at a  $\sim 7$  mag star to provide the guide-2 function.

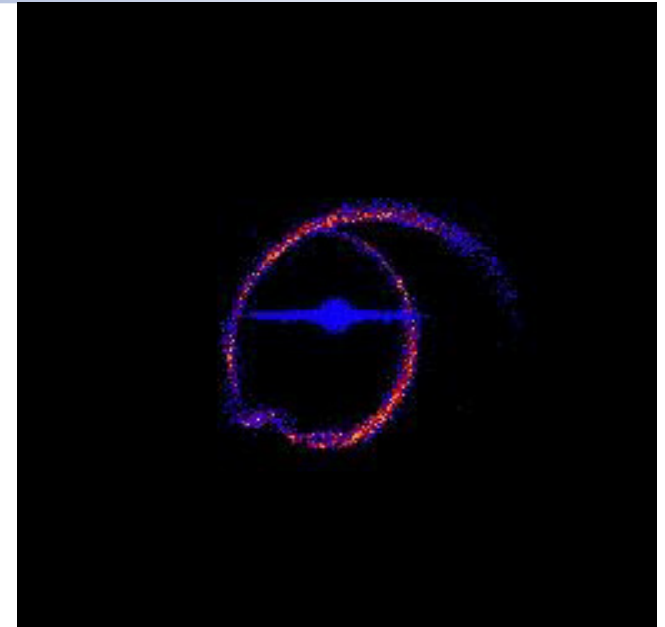


# Astrophysics with SIM



SIM PlanetQuest

- Dark Matter
  - In the halo of the Milky Way
  - Motion of galaxies in the local group
  - Follow up microlensing events (astrometrically, and photometrically)
- Stellar astrophysics
  - Mass luminosity relation of stars (binary star orbits, parallaxes)
  - Masses of Neutron stars/stellar mass black holes
- Measure  $H_0$ , to constrain dark energy



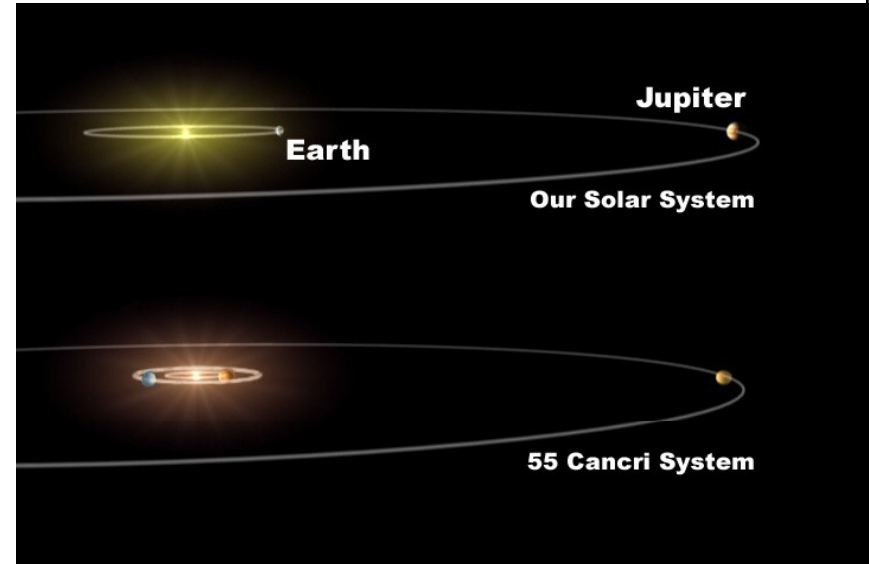
- Tidal tails from dwarf galaxies orbiting the Milky Way provide an ideal probe of the dark matter in the halo.
- SIM provides accurate proper motions (and parallax) of the faint stars in the tidal tails. (to 20 mag)



# Extra-solar Planets Science



- Deep search,
  - (ultra-deep search) look for 1  $M_{\text{earth}}$  planets in the habitable zone, around the nearest 60~100 nearby stars
- Broad survey
  - Search ~2000 stars for planets to ~10  $M_{\text{earth}}$
- Jovian planets around young stars,
  - Young planetary systems that aren't yet dynamically stable.



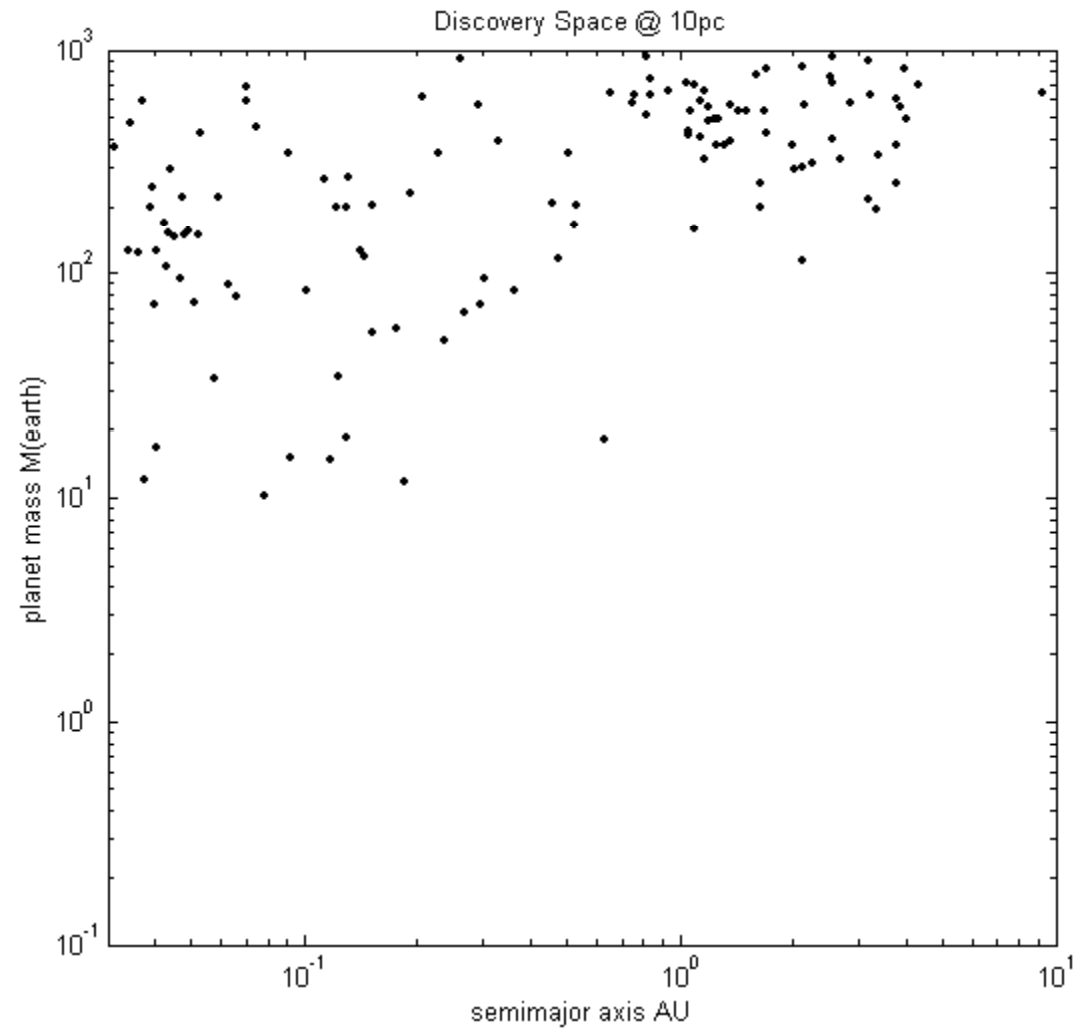


# Extrasolar Planet Phase Space



Current harvest of >250 planets (RV): empirical constraints to planetary system formation.

SIM PlanetQuest



>250 Known exoplanets

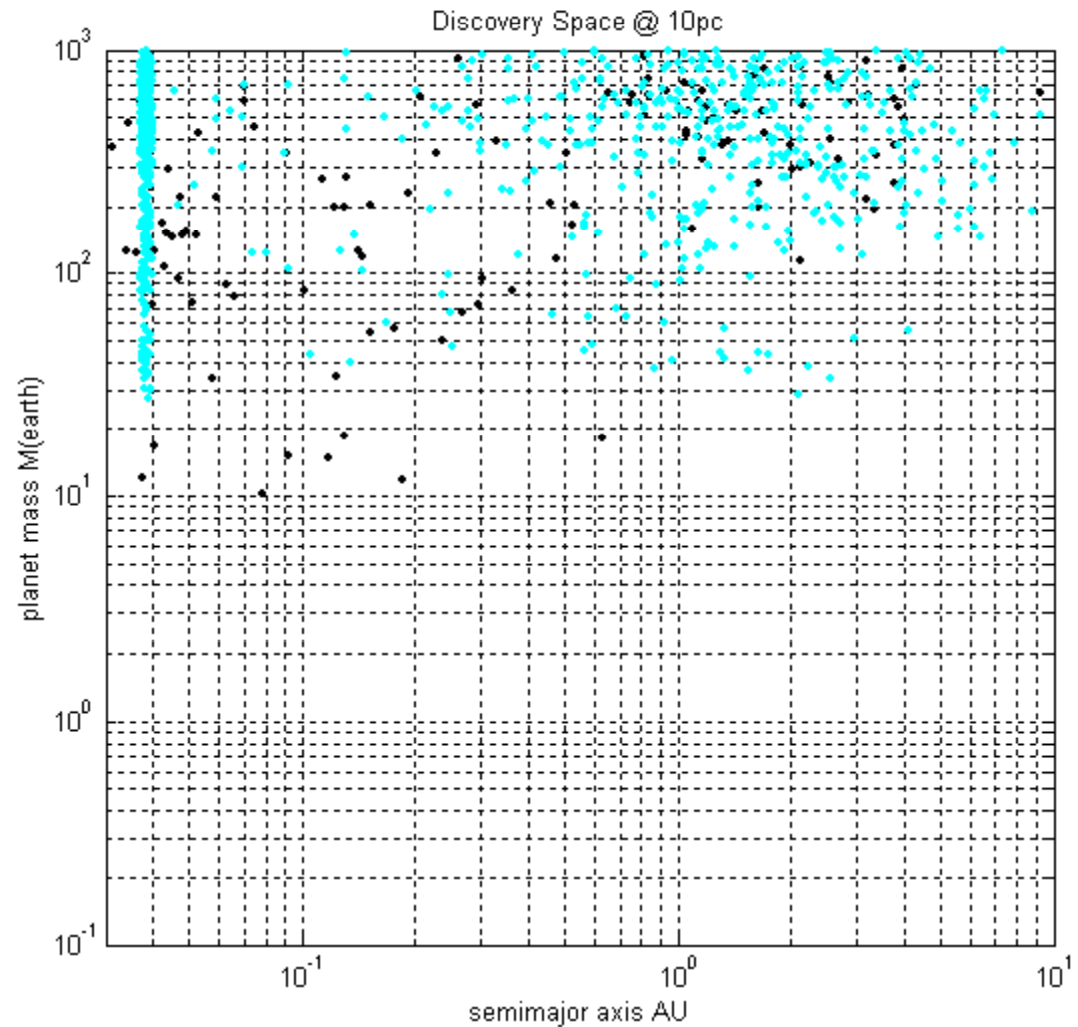


# Extrasolar Planet Phase Space



Current harvest of >250 planets (RV): empirical constraints to planetary system formation.

SIM PlanetQuest



Distribution of Planets from Ida , Lin , 2005ApJ, 626,1045



# Extrasolar Planet Phase Space

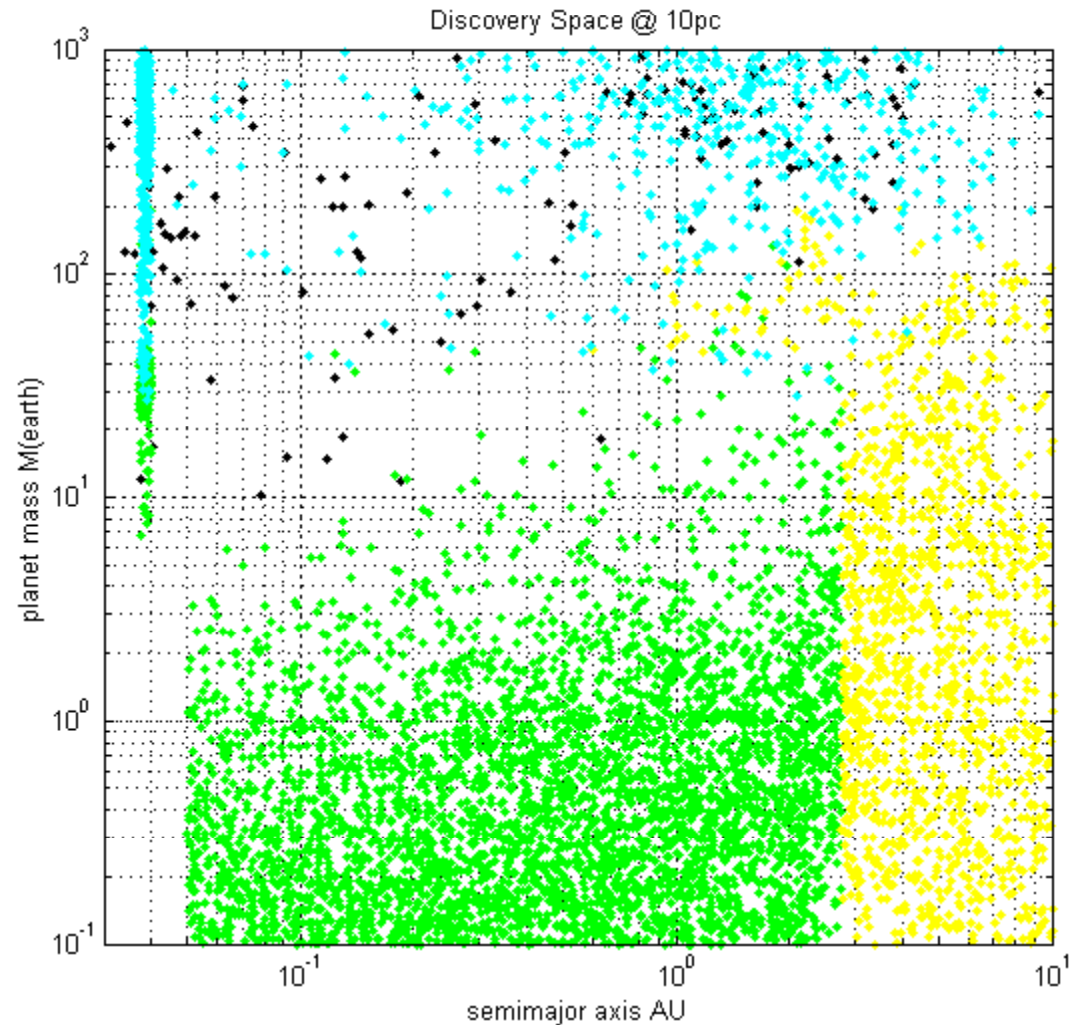


Current harvest of ~200 planets (RV): empirical constraints to planetary system formation.

*Jupiter & Neptune appear to be the tip of the “planetary iceberg”*

*The number of planets grew significantly below 5~7  $M_{\text{earth}}$ .*

SIM PlanetQuest



Distribution of Planet from Ida , Lin , 2005ApJ, 626,1045



# Extrasolar Planet Phase Space

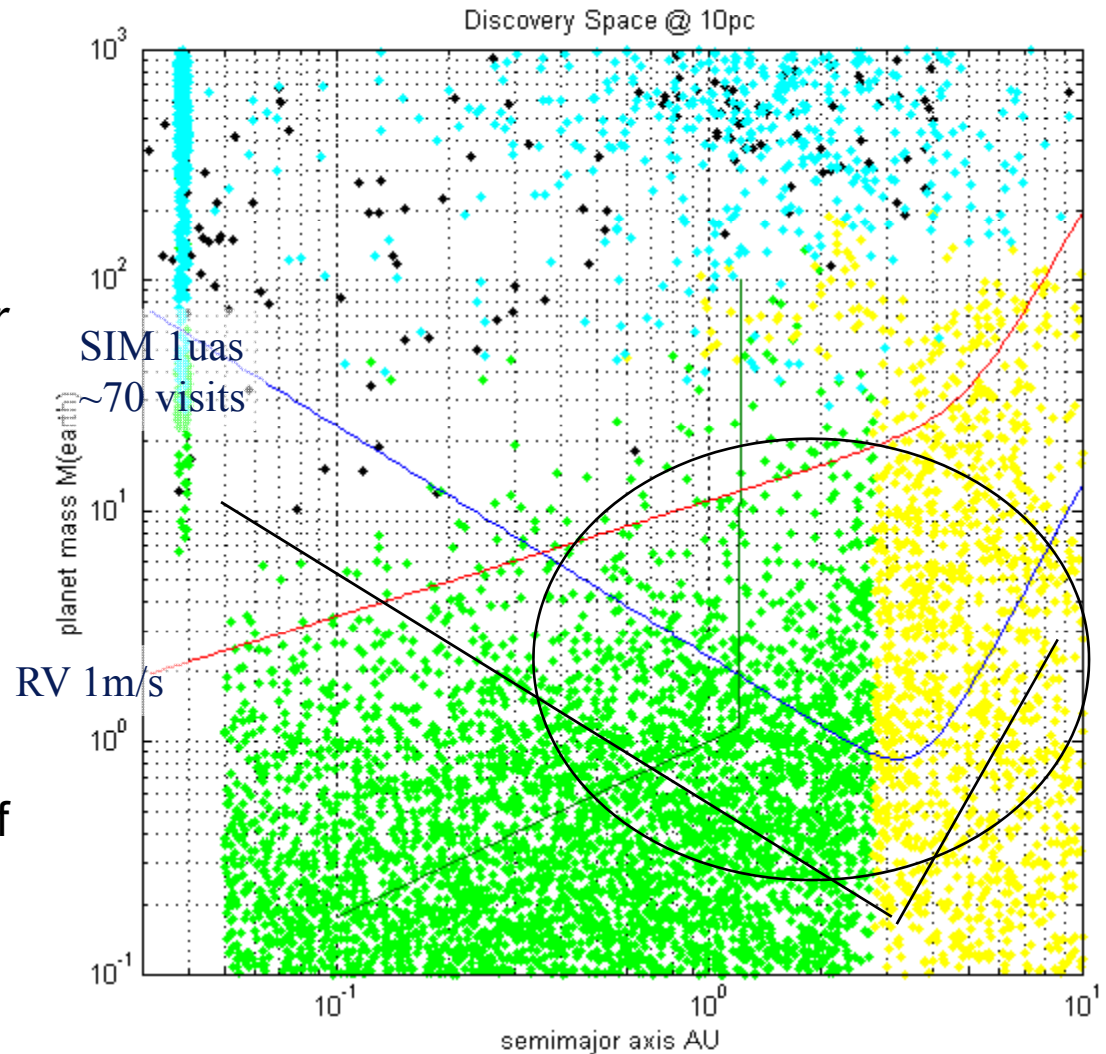


Current harvest of ~200 planets (RV): empirical constraints to planetary system formation.

*Jupiter & Neptune appear to be the tip of the “planetary iceberg”*

SIM: uniquely probes  
 $1 \sim 10 M_{\text{earth}}$  (0.4~6.0AU)  
(for nearby stars)

Inclination and mass for  
RV planets (coplanarity of  
multiplanet systems)



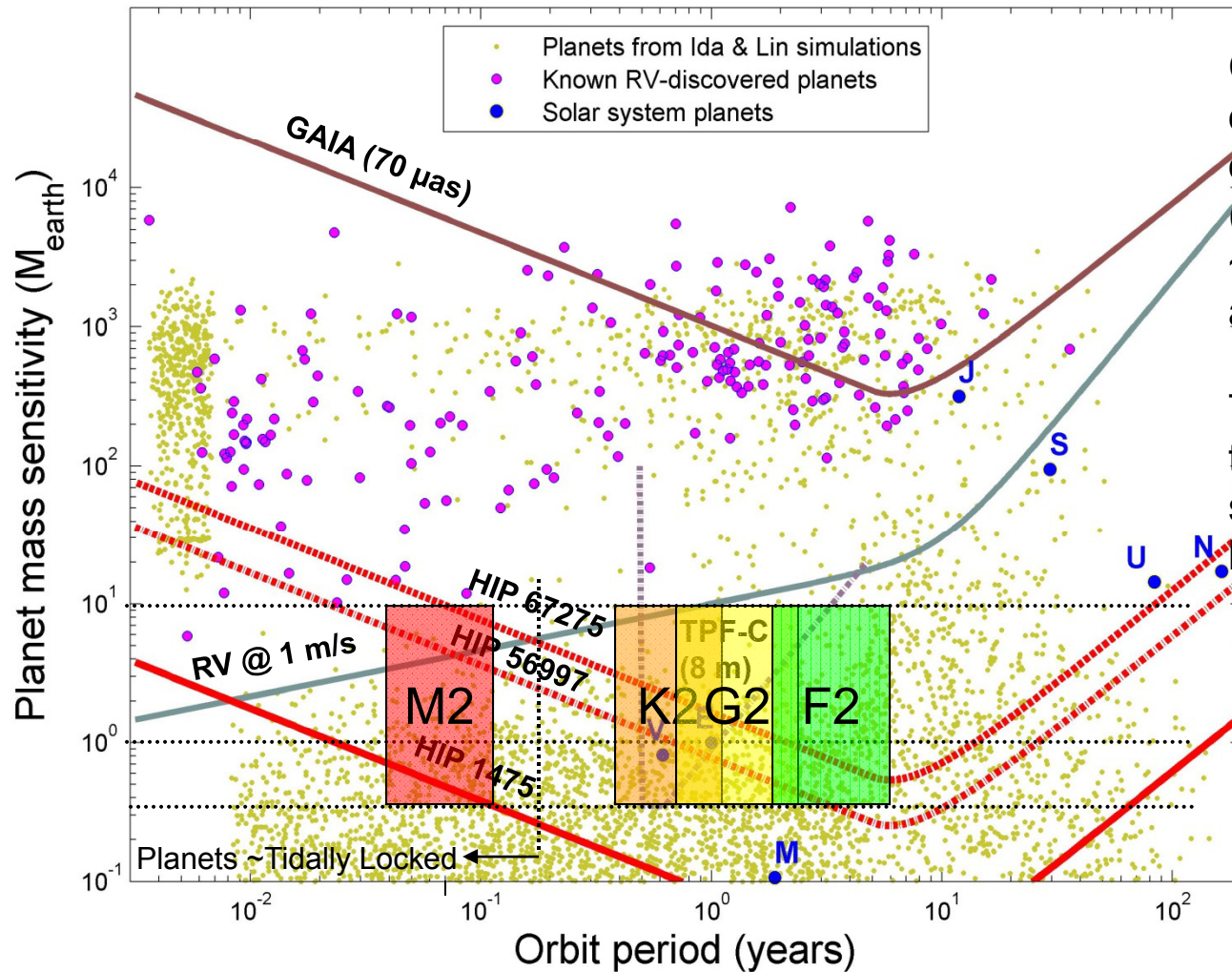
Distribution of Planet from Ida , Lin , 2005ApJ, 626,1045

SIM PlanetQuest



# Ultra Deep Search for Earth Clones

## Exoplanet Discovery Space



Concentrate a lot of observing time 40% on a small number (~130 for SIM and ~60 for SIM-Lite) over a 5 year mission.

To achieve sensitivity to 1 Mearth @ (1 AU) scaled to the luminosity of the star



## Side Issues, Systematic Errors and Star Spots



- An Earth–Sun system at 10pc has an astrometric amplitude of  $0.3 \mu\text{as}$ . Detection of a planet requires a  $\text{SNR} \sim 5$ . The noise of 5 yrs of data has to average down to  $< 0.06 \mu\text{as}$ 
  - $\text{SNR} = \text{amplitude of sinewave} / (\sigma_{\text{1epoch}} / \sqrt{N_{\text{epoch}}})$
  - Laboratory demonstration of  $1 \mu\text{as}$  precision (1100 sec integration)
  - Lab results for long integrations ( $10^5$  sec), and extrapolation to on orbit precision
- At sub  $\mu\text{as}$  levels, we also need to worry about astrophysical noise sources.
  - Planets around ref stars (ref stars are K giants at 700~1Kpc, only large planets matter ( $\sim 0.5 \text{ Mjup}$ ).
    - $\sim 20\%$  of stars have planets  $> 0.5 \text{ Mjup}$ , so on average one of the ref stars for a target will have a planet. This is detectable by looking at “pairs” of stars.
  - Star spots (Next few charts)



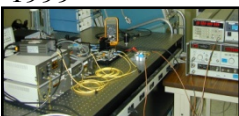
# SIM Technology Flow



SIM PlanetQuest

## Component Technology

1999



Metrology Source

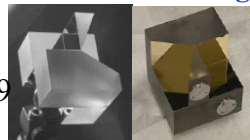
2001



Absolute Metrology

Picometer  
**Knowledge**  
Technology

1999

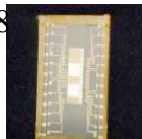


Multi-Facet Fiducials

1:Aug2001

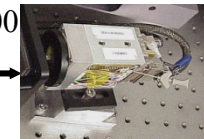
1: Beam Launchers

1998



High Speed CCD

2000



Fringe Tracking  
Camera

Nanometer  
**Control**  
Technology

Optical  
Delay Line

1998



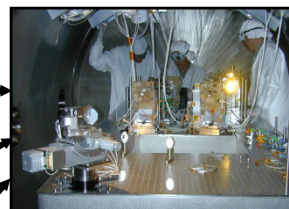
Hexapod  
Reaction Wheel  
Isolator

1998



## Subsystem-Level Testbeds

4:Oct2002



4: Kite Testbed (Metrology Truss)

3:Sep2002; 5:Mar2003

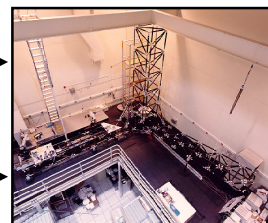
6:Sep2003; 7:Jun2004



3, 5, 6, 7: MAM  
Testbed  
(single baseline picometer  
testbed) Narrow & Wide  
Angle Tests



TOM Testbed  
(distortion of front  
end optics)



STB-1 (single baseline  
nanometer testbed)

1999

## System-Level

8:Jul2005



8: Overall system  
Performance via  
Modeling/Testbed  
Integration

Numbers before box  
labels indicate HQ  
Tech Gate #'s (1  
through 8)

All 8 Completed

2:Nov2001



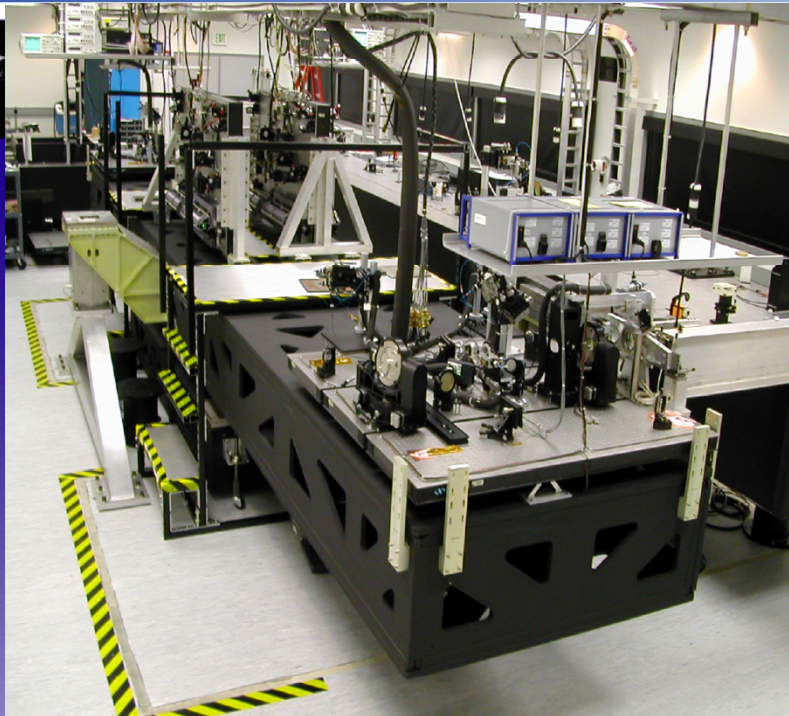
2: STB-3 (three baseline  
nanometer testbed)



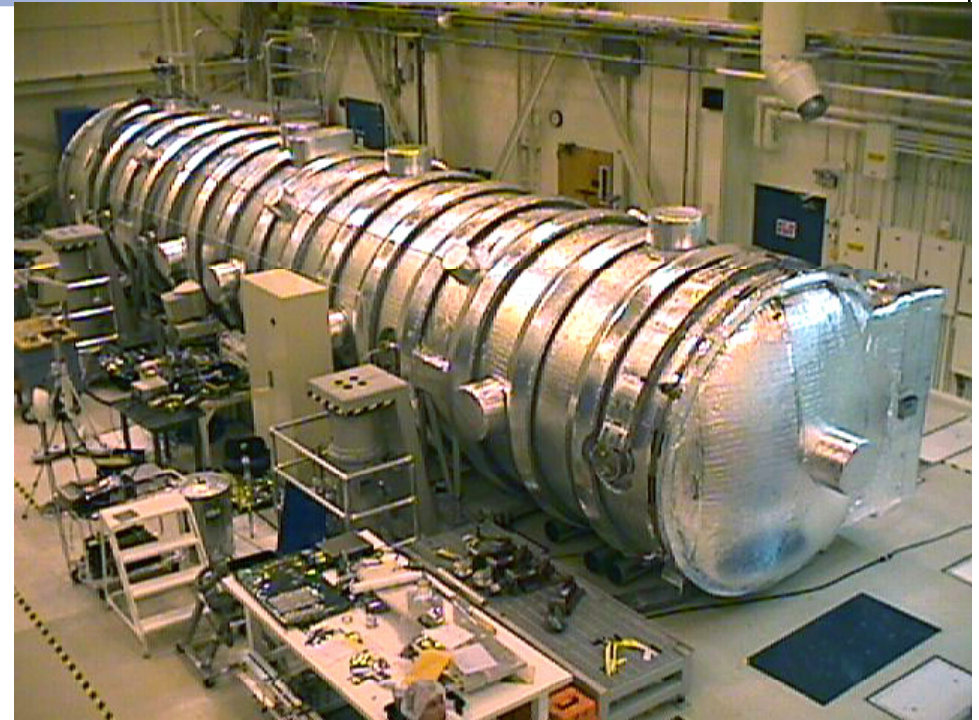
## Large Testbeds, STB-3, MAM



SIM PlanetQuest



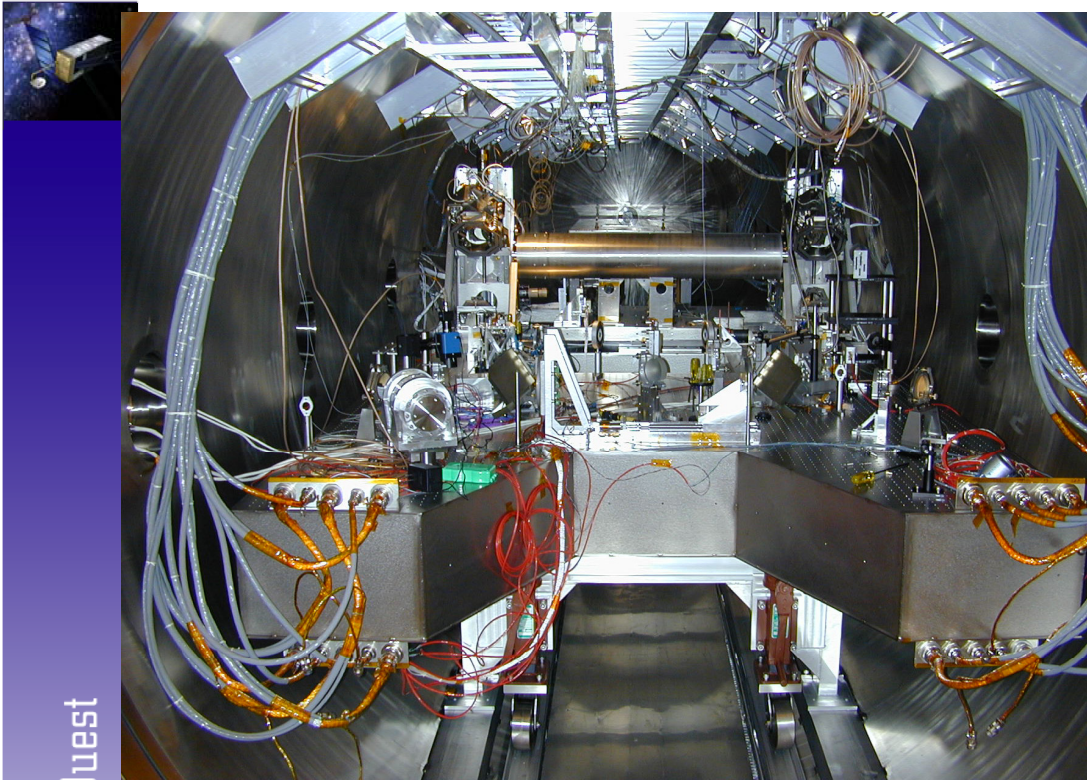
- Nanometer control testbed
  - Full scale 9m long
  - Structure (lowest resonance) similar to SIM.
  - Simulated vibration source (reaction wheels and isolators)
  - Simulated ACS error (pseudostar on adjacent optical table moved with voice coils)



- MicroArcsec Metrology testbed
  - All sub-nanometer metrology tests have to be conducted in vacuum

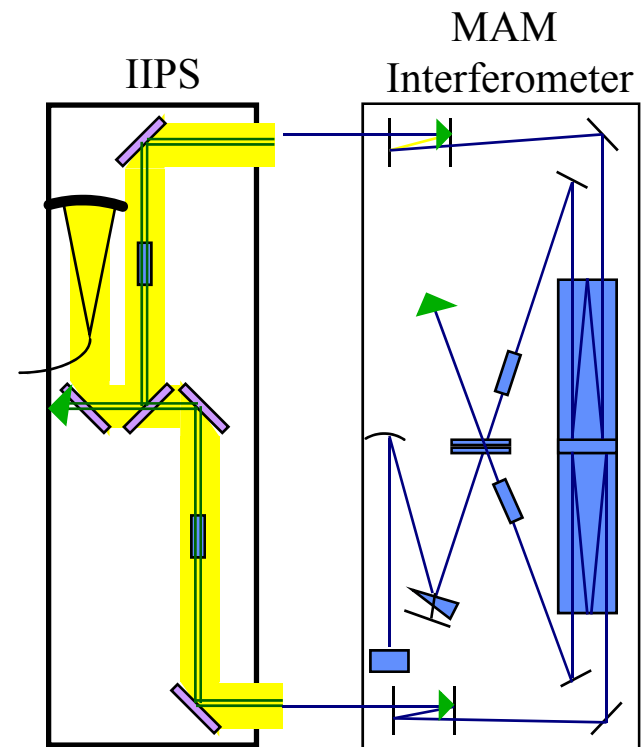


# The Micro Arcsec Metrology Testbed



Laser metrology measures the position of the IIPS.

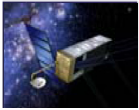
Test is to compare metrology to whitelight (starlight) fringe position.



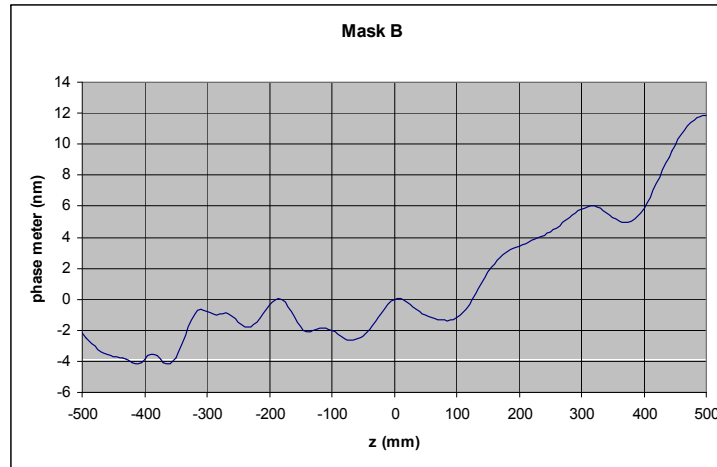
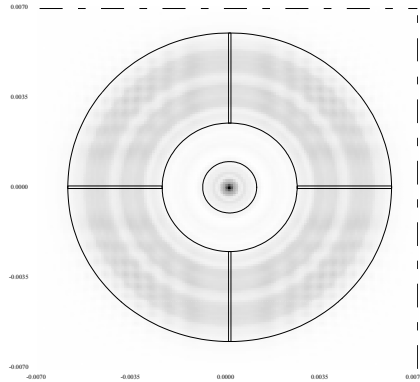
The pseudo-star moves over a 1deg for narrow angle tests (15deg for wide angle tests).



# Examples of Systematic Errors



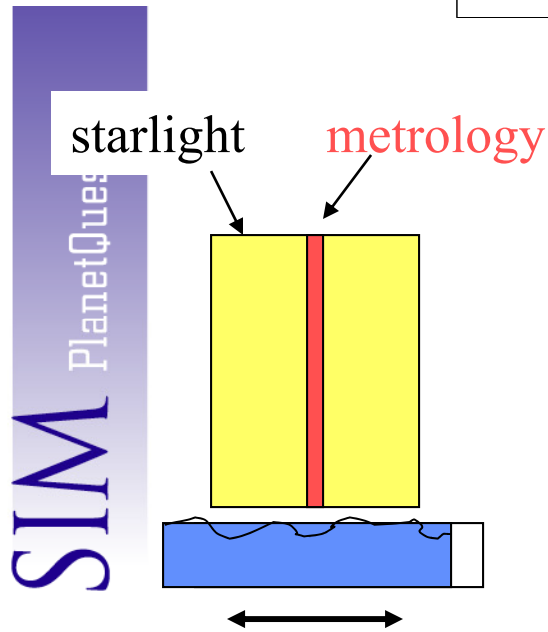
SIM Diffraction Testbed  
TEMPORARY STORAGE 1



Diffraction:

The metrology beam and starlight beam are different diameters, see different obscurations.

After propagating ~10 meters the optical phase of the wavefront of metrology and starlight are different



Beamwalk:

The metrology beam samples a different part of the optic than the starlight beam. If the optical surface is perfect at  $\lambda/100$  rms, the surface has 6nm hills and valleys.

If we want to measure optical path to 50 picometers we have to make sure we sample the same hills and valleys everytime.



# Narrow-angle Astrometric Observations

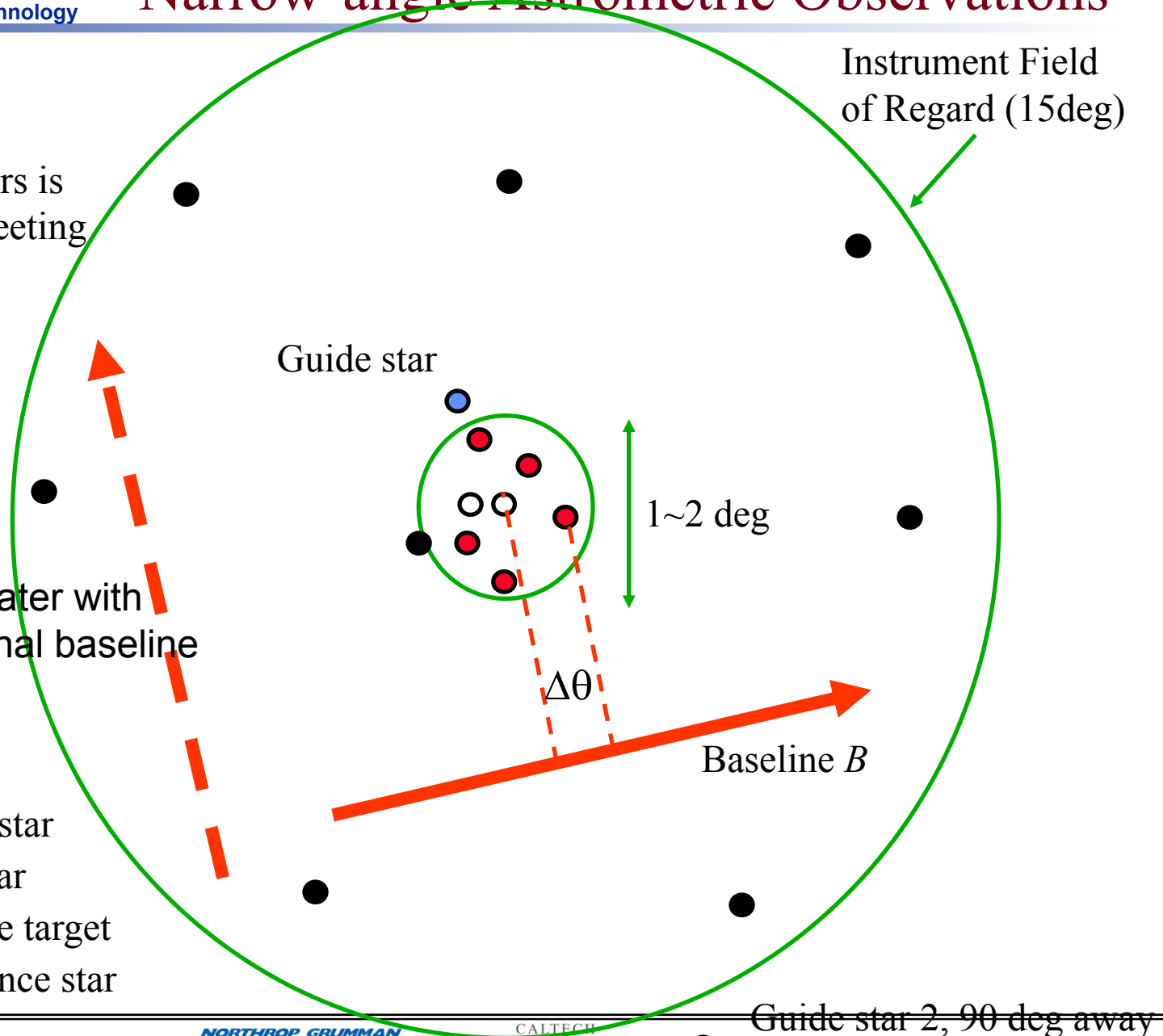


Understanding  
instrument  
systematic errors is  
essential for meeting  
narrow-angle  
performance at  
1  $\mu$ as accuracy

SIM PlanetQuest

Repeat later with  
Orthogonal baseline

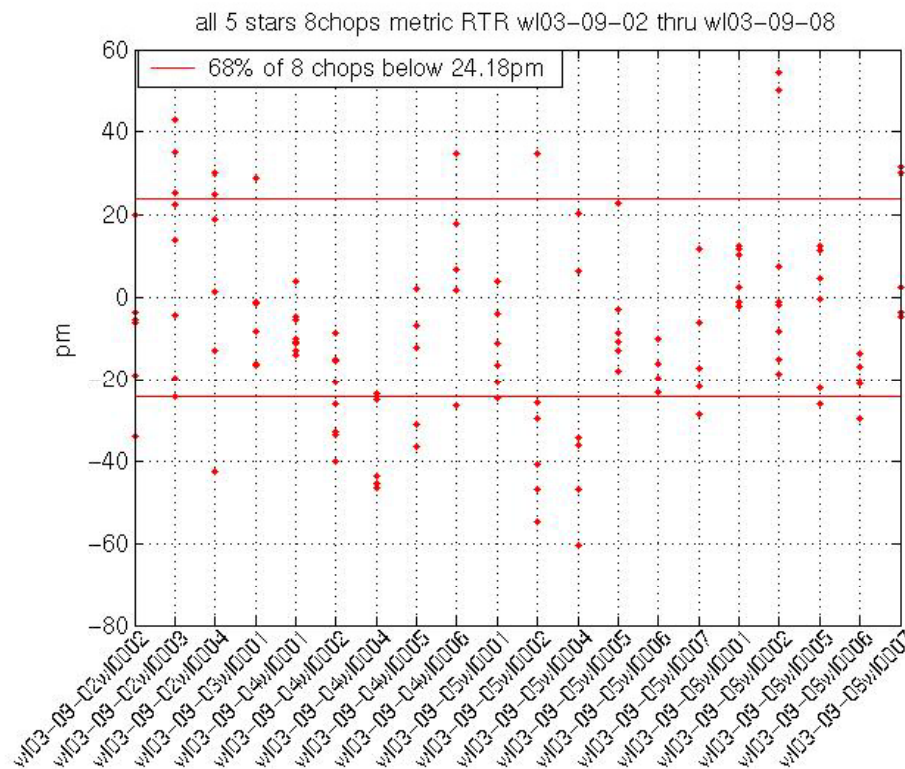
- Guide star
- Grid star
- Science target
- Reference star



## Sqrt(N) From 1 Chop to 8 chops

MAM test: 4 ref stars, 1 target star, (T, R1, T, R2, T, R3, T, R4 .... Repeat)

~20 runs conducted over ~1 week.



1 was total error  
0.7 to photon noise  
0.7 to instrument  
0.5 to science interf

0.5uas ~25 pm

## Meet 25pm in 8 chops

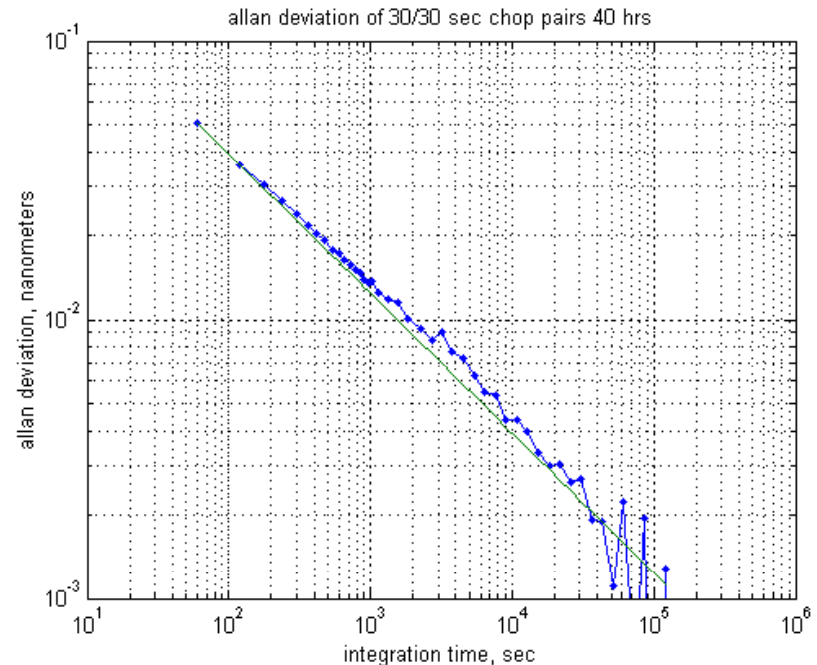
Each dot is an 8 chop  
average



# Chopping in the MAM testbed



- Thermal drift affects all measurements
- For narrow angle observations, w “chop” between target and reference stars every 90 sec.
- When this observation procedure was tested in the MAM testbed w showed that thermal drift noise became “white” after chopping.
- The remaining question, is the thermal drift in the MAM testbed, representative of the thermal stability we will see on SIM in orbit?

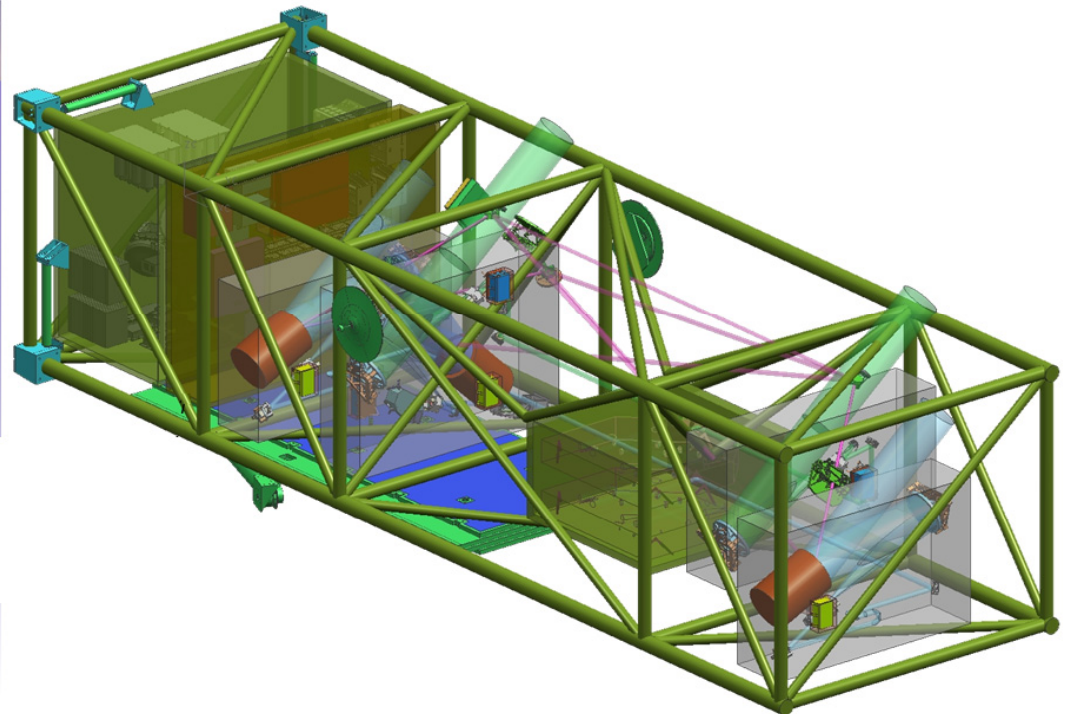


$$\underline{1\text{pm}/9\text{m} = \sim 0.025\text{uas}}$$



# Thermal Drift, 1/f type noise

- Thermal drift will change optical pathlengths. But **most thermal drift on SIM is benign**, because it's **accurately monitored by laser metrology**. (accurate means accurate at the few picometer level)
- **Astrometric errors occur when the alignment of the starlight and metrology light diverge**. Since both starlight and metrology light are actively control, this happens when the alignment sensors in the ABC (astrometric beam combiner) move wrt each other.
- Dimensional instability (from thermal instability) of the ABC bench can cause star-light and metrology to diverge.
- ABC bench is a box within a box. The ABC enclosure is controlled to 10mK/hr. The ABC optical bench inside the enclosure is stable to better than a few mK/hr.

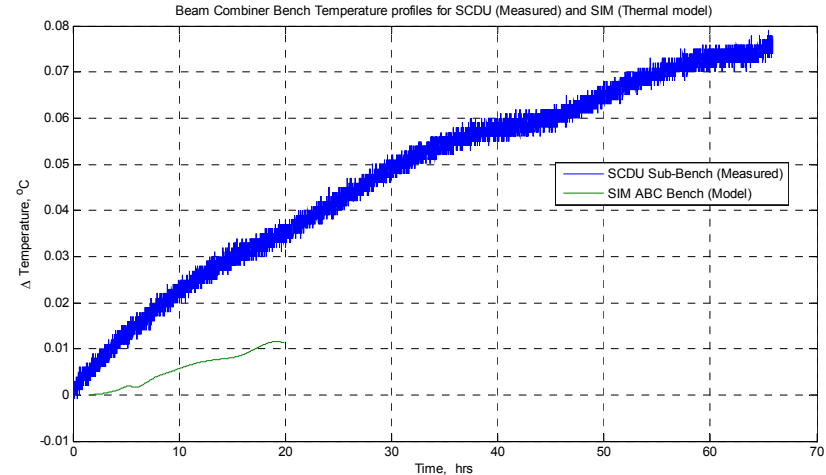
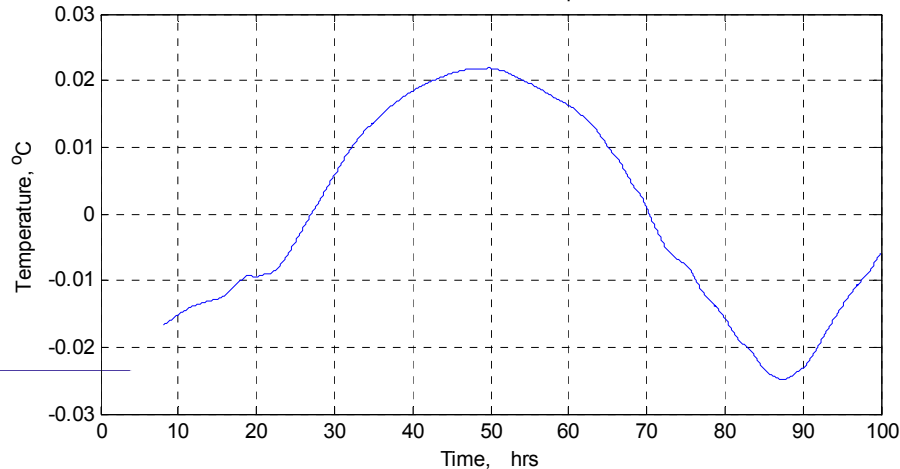




# Thermal Stability of the Lab Testbed vs Model of SIM on Orbit



SIM Thermal model of ABC Bench temperatures over 100 hrs



Multi-100 node thermal model of SIM-(lite) in solar orbit executing an orange peel. Plot is temperature on the ABC bench.

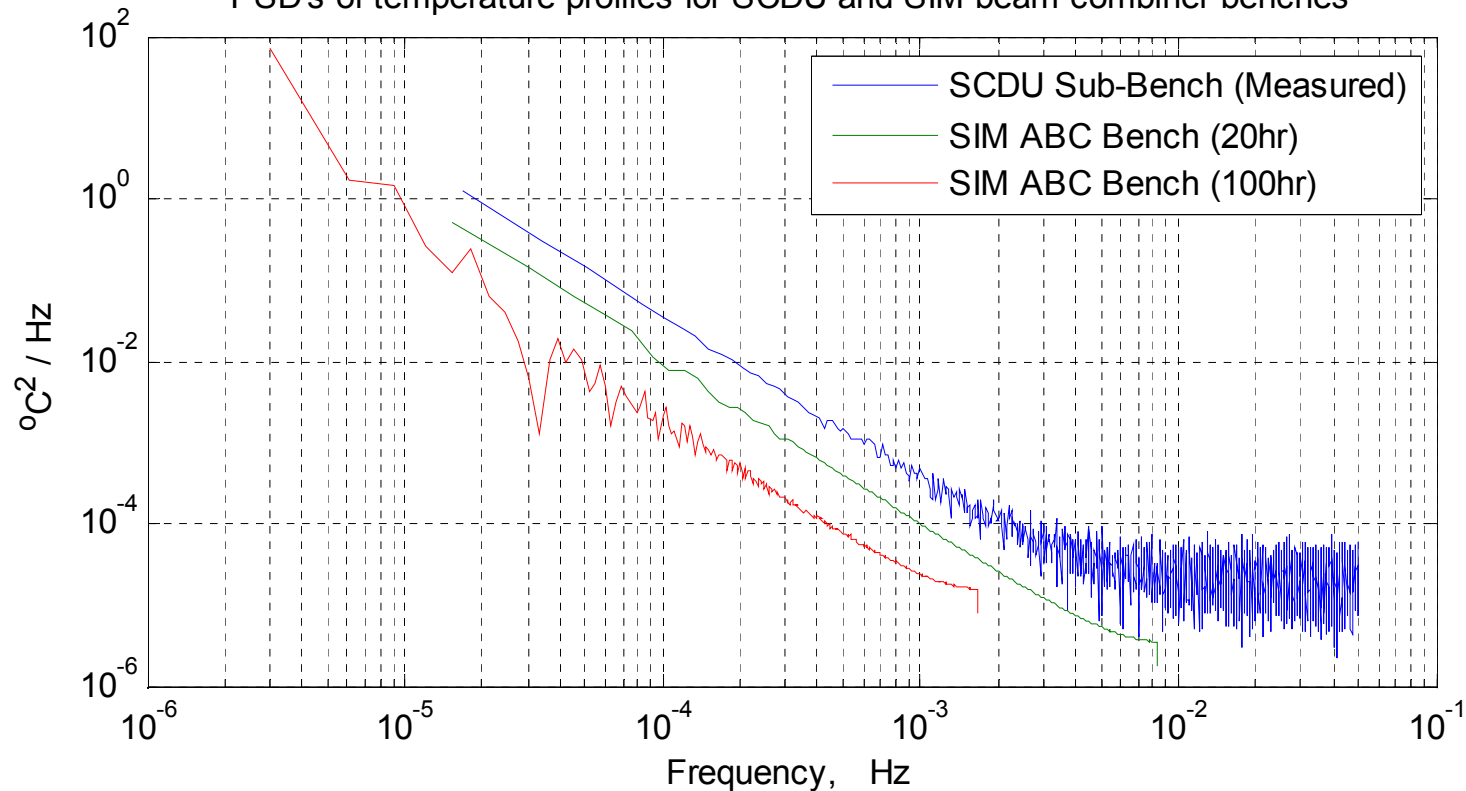
Inside Testbed Vac Tank temperature measurement

The MAM optics in the MAM vacuum chamber was reconfigured and the testbed called SCDU. But the thermal properties of the chamber were overall unchanged. (Shorter ~6hr allan variance data taken showed that the new setup is slightly better than before.

SIM



PSD's of temperature profiles for SCDU and SIM beam combiner benches



We have two squiggly lines for thermal drift. How do we compare them? We compare their power spectra.

SIM in solar orbit is expected to be more stable than the inside of the MAM vacuum tank. (Thermal instability even in the MAM tank is not the dominant error/noise source.)

The reason chopped astrometry error goes as  $\sqrt{T}$  is because we're sensitive to the noise at  $\sim 1\text{e-}2$  hz, (90sec chop period). The rms error of a 1000sec integration of a chopped signal is roughly a 0.001hz bandwidth around 0.01hz.

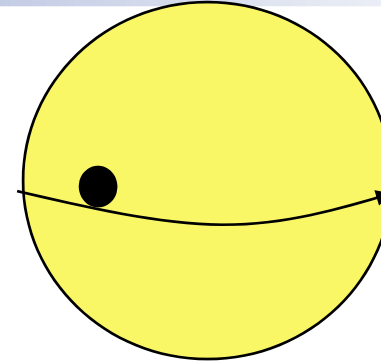


## Star Spots

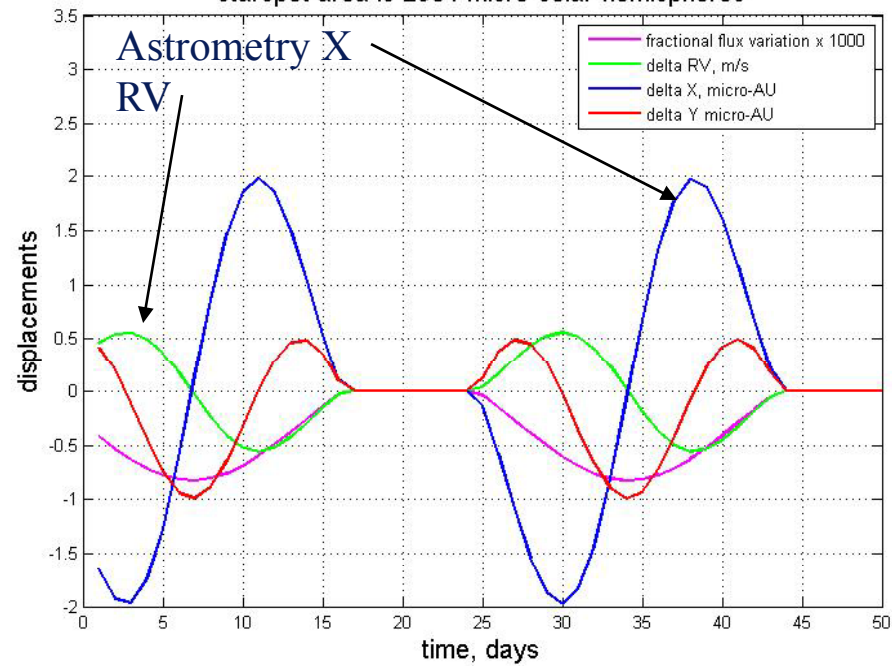


SIM PlanetQuest

- Not all stellar variability results in an astrometric bias.
  - Uniform expansion of the star will cause an RV error, but no astrometry error.
- Spots (or bright areas around spots) will affect both RV and Astrometry much the same way.
- Our approach to estimating the astrometric and RV noise from star spots is through a simulation, where spots are randomly created, and decay.



Flux, RV and centroid signature of a dark starspot at latitude -30 deg on a solar-type star at inclination 45 degrees  
starspot area is 2584 micro-solar-hemispheres

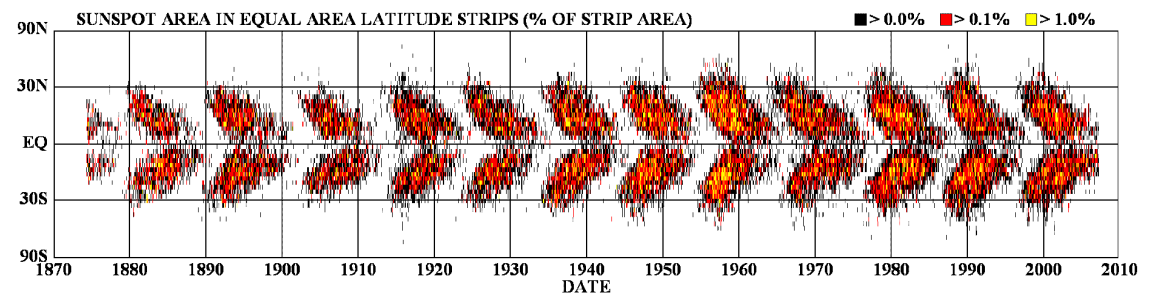




## Model/Simulation

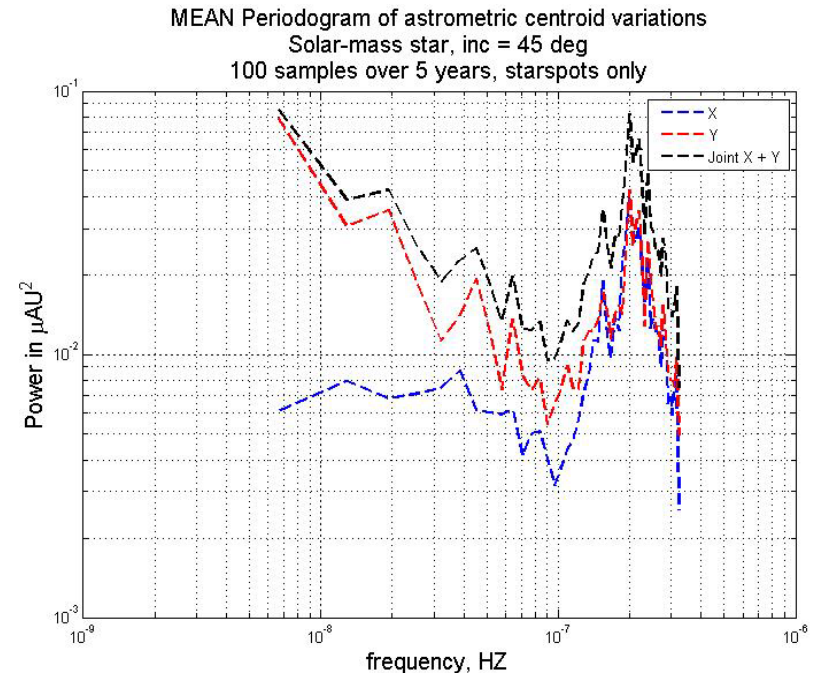
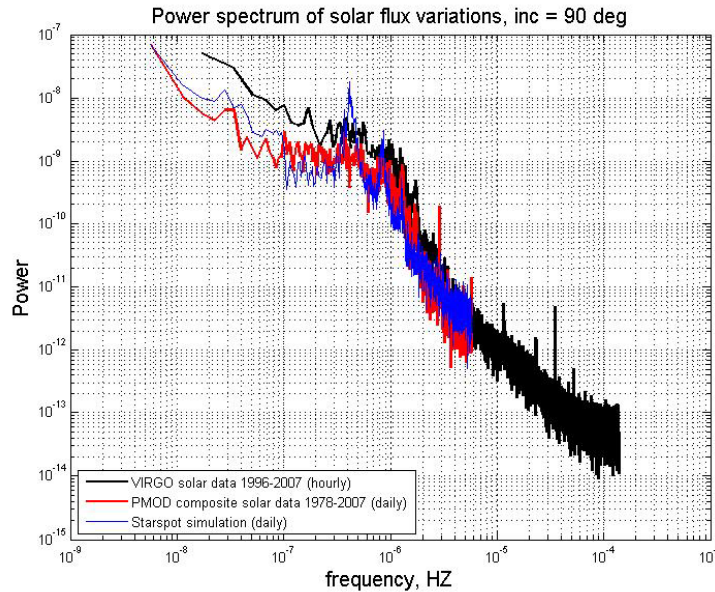


- The spots are characterized by creation time, size, lifetime, and latitude. (The number of spot vs latitude is roughly constant with the 11yr sunspot cycle).
- From this model we can calculate the power spectrum of
  - RV error due to spots
  - Astrometric error due to spots
  - Photometric variation.
    - We tweak the model so that the power spectrum of the photometric variations match the power spectrum of  $\sim 30$  years photometric monitoring of the Sun from space (Acrim, Virgo)





# Photometric, Astrometry Power Spectra



- The spot model was used to generate astrometric noise, over a 5 year period, and would produce noise at 0.05 Mearth. (5 sigma detection would be possible for planets > 0.3 Mearth.)
- Spot noise is small, RSS'd with stellar photon & instrument noise

Example	Astrometry	RV
Earth-Sun @ 10pc	0.3 uas	0.1 m/s
1e-3 star spot @45deg	0.25 uas	1.0 m/s
spot noise is correlated ~1/2 rotation period		



## Reducing the Cost of SIM



- For a number of reasons, it would be desirable to reduce the cost of the mission.
- Hardware changes
  - Reduced mass by ~2000kg
  - Reduce launch vehicle size
  - Shorten baseline (performance and thermal vac in JPL chamber)
  - Technology is mature (because of delays in getting project approval) schedule and reserve reduced.
- Operations (phase E) Changes, no longer operated like a great observatory

SIM PlanetQuest



# SIM and SIM-''Lite''



SIM PlanetQuest

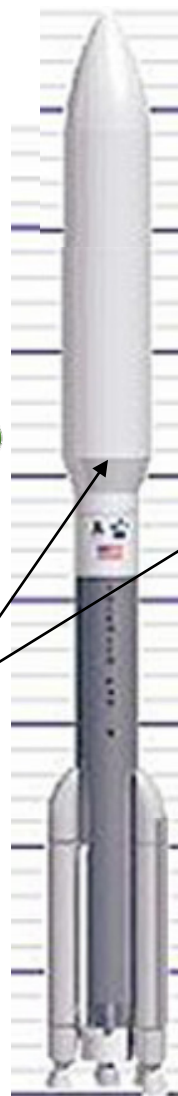
Parameter	SIM-PQ	SIM-LITE
Wide Angle (global) accuracy	2.4 uas	3.6 uas
Narrow Angle Accuracy	0.7 uas	1.0 uas
Mag limit	20 mag	20 mag
# Stars surveyed 1Mearth-HZ	~130	~60
Mass (with reserve)	6800 KG	4300 KG
Number of Interferometers	3	2
Science Baseline	9m	6m
Guide-1 Baseline	7.2m	4.2m
Guide-2	7.2m	0.3mTscope
Launch Vehicle Atlas V	551	521
Payload Risk Class	A	B
BCD schedule	77 mon	58 mon
BCD cost to go	1470 M	940 M
Mission Ops 5yrs	400M	170 M

Smaller size also meant end to end performance test of flight hardware could be done in thermo-vac chamber at JPL, instead of S/C contractor.

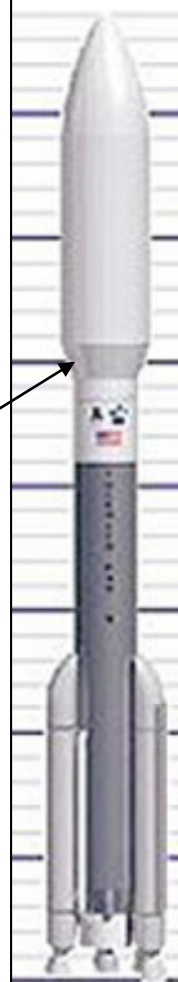


Note: Centaur upper stage used in both vehicles.  
-Inside fairing.  
-ETSO orbit

SIM  
PlanetQuest



Atlas V  
551



Atlas V  
521

SIM-  
''Lite''

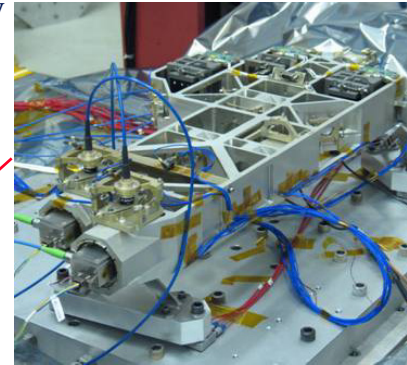




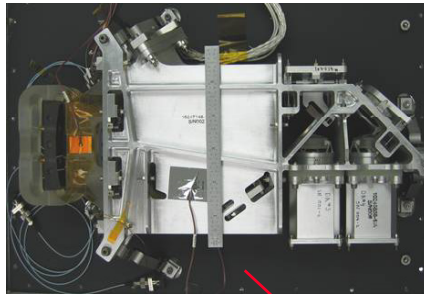
# From Technology to Flight Component Engineering

- Much of the SIM hardware for flight already exists in engineering model and brassboard form.

Metrology  
Source



External  
Metrology  
Launcher



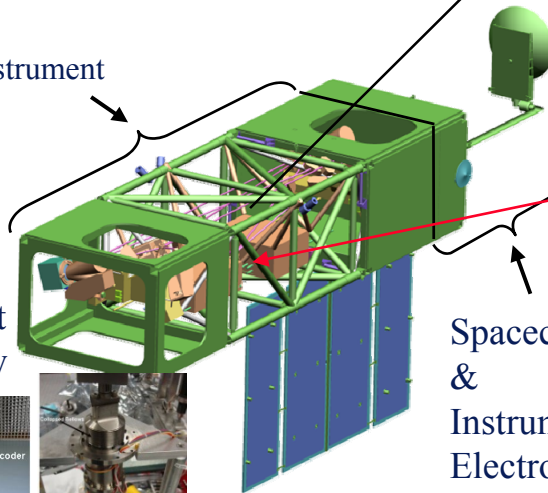
Fast Steering  
Mirror



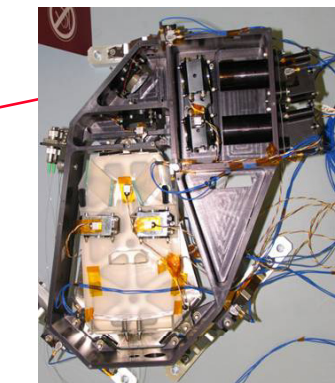
Astrometric Beam Combiner  
(Drawings released)



Instrument

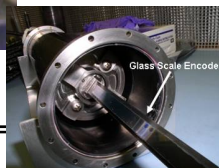


Spacecraft  
&  
Instrument  
Electronics

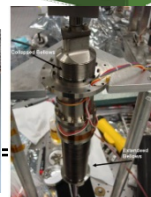


Internal Metrology  
Launcher

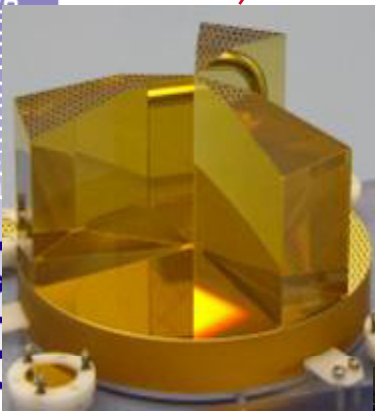
Siderostat  
ball screw



Glass Scale Encoder



Double Corner  
Cube





# Applying SIM Technology to Direct Detection



SIM PlanetQuest

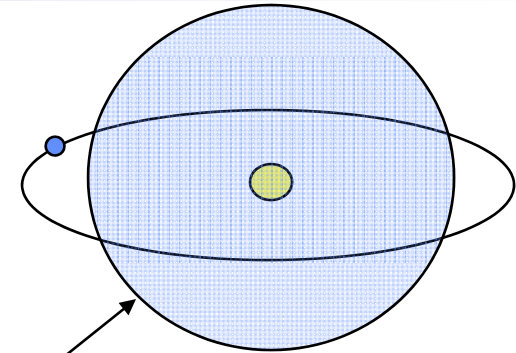
- The exoplanet task force report,
  - [http://www.aura-astronomy.org/nv/Lunine\\_ExoPTFInterimReport.pdf](http://www.aura-astronomy.org/nv/Lunine_ExoPTFInterimReport.pdf)
  - Recommended an astrometry mission to find the nearby terrestrial planets to give “addresses” of Earths for a subsequent Direct Detection mission that will detect the light, and measure the spectra from the planet.
    - Detect the presence of oxygen, water vapor, etc. constituents of an atmosphere that might indicate the presence or possibility of life.
- What are the challenges of detecting the light from an Exo-Earth? What are the cost drivers? Why/how would astrometric mission help a follow on direct detection mission?
  - Huge contrast Sun-Earth contrast  $10^{10}$  @ 0.1 arcsec separation
    - Much lower contrast @  $10\mu\text{m} \sim 10^7$ , but the much larger aperture/baseline needed was extremely expensive
  - High contrast at very small angle is a huge technology driver, as well as a huge cost driver. NASA issued an NRA for mission concept studies



# Inner Working Angle and Planet Observability



- The diff limit of a telescope is  $\lambda/D$ , but if the contrast is  $10^{10}$ , the star-planet separation has to be a bit larger.
  - A factor of 2 is a big deal, it's the difference between a 4m and 8m space telescope. (with  $\lambda/10000$  wavefront control)
- If the maximum star-planet separation is the IWA, the planet will only spend a small fraction of its orbit outside the IWA. Effectively undetectable.
  - Knowing the planet's orbit, one can use a  $\sim\sqrt{2}$  smaller telescope. Even  $\sqrt{2}$  is a big deal.



IWA (inner working angle)

Lyot type coronagraphs  $\sim 4 \lambda/D$

Exotic coronagraphs  $2\sim 2.5 \lambda/D$

External occulters (different rules)

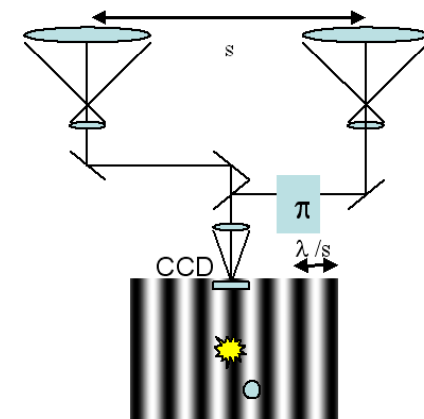
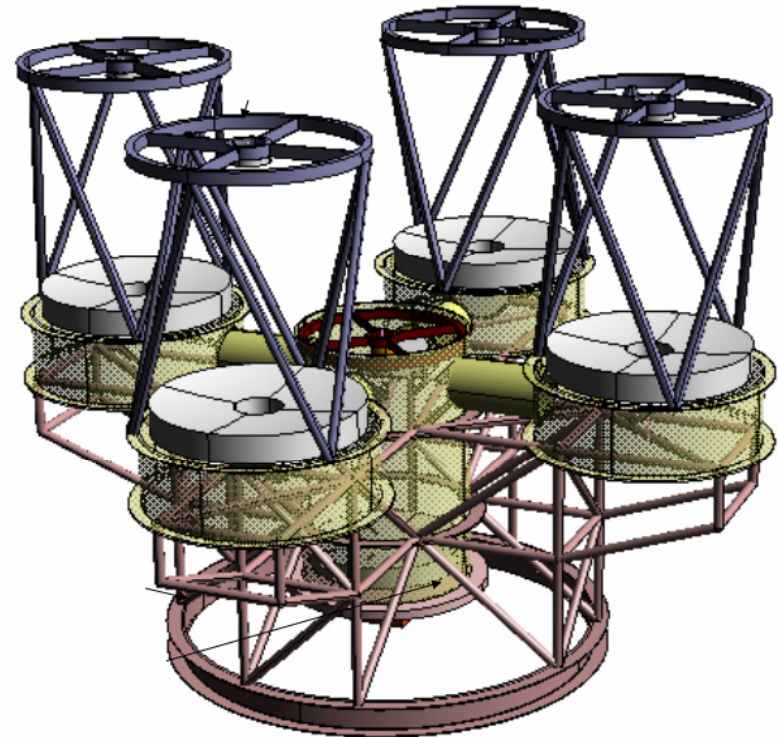
If IWA=70mas  
 $\lambda = 780\text{nm}$  (oxygen)  
 $2.5 \lambda/D = 70\text{mas} \Rightarrow D = 5.7\text{m}$



# A Dilute Aperture Coronagraph



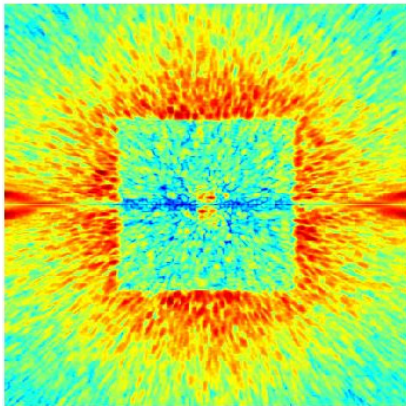
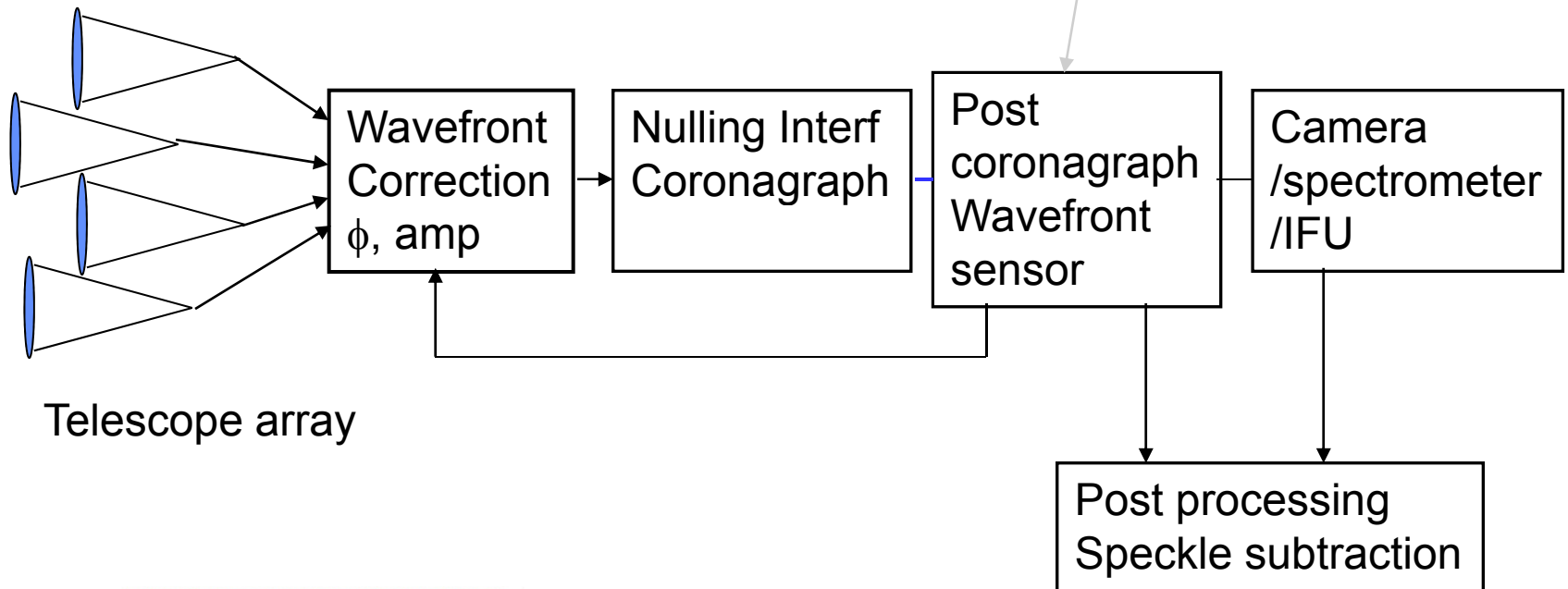
- Why a dilute Aperture, why visible?
  - Small Inner Working Angle, with moderate cost.
  - Cost of 4 1.1m telescopes
  - Inner Working Angle of a 5 m coronagraph.
- Cost of space telescopes has been studied by many experts. (Meinel, B etc.)
  - Cost  $\sim D^{2.5}$
  - Cost of associated spacecraft follow the cost of the telescope.
  - **Potential 5~10X reduction in cost** of a coronagraph that can detect  $\sim 100$  Exo-Earths (if they exist)
  - Integration time equiv to  $\sim 2m$  coronagraph,





## Block Diagram

Same wfs as used in  
Gemini Planet Imager (UCSC)



Local + Exo-zodi  $\sim 10^{-9}$   
Starlight suppressed  $< 10^{-9}$   
Residual speckle pattern must  
be subtracted to  $2 \times 10^{-11}$ ,  
for a SNR  $\sim 5$  on a  $10^{-10}$  planet

SIM PlanetQuest

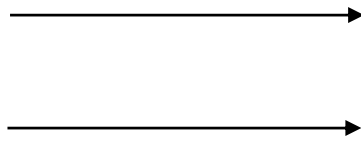


# Precise Phase and Amplitude Control



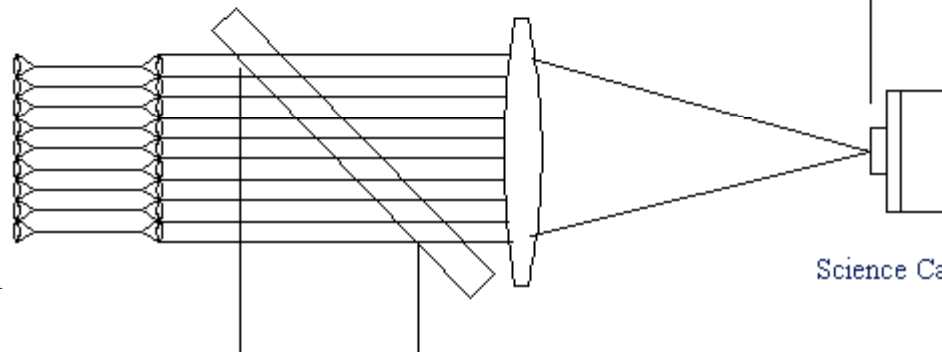
SIM PlanetQuest

Nulling Interferometer  
Output (collimated beam)



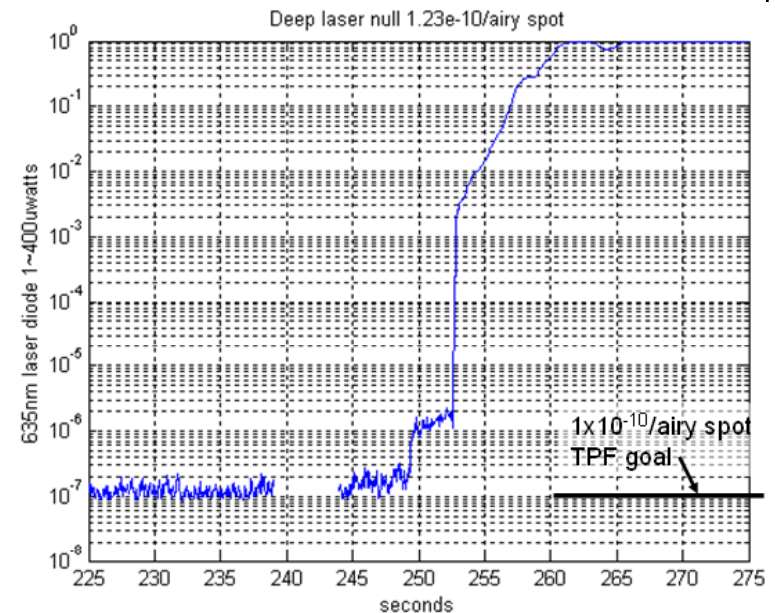
$$10^{-6} \Rightarrow \delta\phi \sim 10^{-3} \text{ rad} \sim 0.1 \text{ nm}$$

Coherent array of  
Single mode fibers



Science Camera

- The pupil is split by a lenslet array  $\sim 1000$  lenslets. The light focused into an array of single mode fibers.
- Inside the fiber, only 2 quantities matter, amplitude and phase. If these are matched, no light will exit the fiber.
- If the f and amp mismatch results in  $\sim 10^{-6}$  leakage, then at the science camera image plane, the average scattered light of  $10^{-6}$  will roughly uniformly cover the  $\sim 10^3$  airy spot field of view resulting in a scattered light level of  $10^{-9}$ /airy spot.





## Summary



SIM PlanetQuest

- SIM-"lite" is much reduce cost version of SIM that still retains the potential to detect Earth Clones around  $\sim 60$  of the nearest stars. ( $\sim 1.1$ B in fy08 \$, this includes 5 yrs of mission operations)
  - It's possible that we would get better science searching 240 stars for 2 Mearth planets, but the capability exists to get to 1 Mearth @ 1AU.
  - Find addresses for the nearest potentially habitable planets
  - Most of the astrophysics is preserved. (the loss in baseline length is partially made up for in the increased collecting area 50cm vs 30cm)
- The technology for SIM is ready. Flight designs and models exist for many flight picometer level precise components.
- The AMCS NRA awarded 6 grants for Visible coronagraphic concepts. (two of them nulling interferometers) The concept makes possible a very large reduction in cost for a follow on mission to characterize exo-terrestrial planets in the habitable zone.



National Aeronautics and Space  
Administration  
Jet Propulsion Laboratory  
California Institute of Technology

# Backup



SIM PlanetQuest

